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Experimental Investigation on Wear Behavior of Epoxy-TiO_2 Composite Coatings via Taguchi Technique

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Abstract: In this study, the weight percentages of various composites are added to epoxy resins coating material with a fixed amount of ceramic particles in order to improve the coating's mechanical and tribological qualities. Prepared were test specimens of pure epoxy resins with varying reinforcement weight percentages (4%, 6% and 8%). The configuration of a Tribometer is used to examine the material's wear characteristics by conducting various tests on a polymer matrix composite. The results obtained indicate that the mechanical and tribological properties of the newly created epoxy coating composite are greatly enhanced by the addition of TiO_2 (titanium dioxide) reinforcement material. This article summarizes the parametric effects of reinforcement, temperature, and load on the wear rate of an epoxy coating with TiO_2 reinforcement. For modeling and optimization, the Taguchi technique is utilized. On a Tribometer with variable load and temperature, the wear resistance of a specimen was examined. According to the data, both reinforcements in epoxy resins result in a lower wear rate than pure epoxy. Analysis of variance (ANOVA) was conducted to determine the significance of the operating parameters on the performance characteristics under consideration. Further experimentation has been conducted to validate the performance of optimal parameters. The proper set of process parameters has been selected based on the findings of this investigation. ANOVA was utilized to examine the influence of each parameter on wear rate. Finally, a confirmation test was conducted to compare the projected wear rate value to the experimental value.

Introduction

Powder coating techniques are utilized in the majority of production-related fields to create protective coatings. Powder can be created to offer a protective surface and durability, as well as to obtain increased hardness, chemical resistance, and a surface that retains its gloss (Selim et al., 2018; Seidi et al., 2020; Pélissier and Thierry, 2020; Maddu et al., 2021). With the aid of automation, powder coating may be applied to hot and cold substrates in corrosive and high-pressure environments. The automobile industry, for instance, employs powder coating to protect under-hood components from extreme temperature and pressure environments (Deng et al., 2018; Giampieri et al., 2020; Sing et al., 2021). The surface finish of powder coating makes the wheel, mirror frame, oil filter, and coil spring all better. Powder coatings are not only being used as primers for topcoats but also as strong topcoats. Some appliance companies replace the energy-intensive process of adding a porcelain surface to washing machine tops with scratch-resistant powder coatings that are framed in a certain way (Selim et al., 2018; Singh et al., 2020). Powder coating is now used on parts of appliances like range dryer drums, housings and the inside and frame of microwave ovens.

Epoxy is the most widely used thermosetting resin for adhesives, coatings, semiconductor encapsulation, hardware components, electronic circuit board materials, aerospace, and composite matrix (Singh et al., 2018; Kumar et al., 2019; Zhao et al., 2022; Dallaev et al., 2023; Tokunaga et al., 2024). This is because epoxy has high-performance characteristics like tensile strength,

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Table 1. Tribometer Specification.

Make Model	Ducom Ltd., Bangalore, India
Specification (Upper)	Pin (dia.1): 4, 6, 8, and 10 millimeters (15 millimeters). rectangular pin (lbh) 4, 6, and 15 Pin Square (lbh): 4x4 mm, 6x6 mm, and 8x8 mm. Ball-10 mm
Lower Specification	Block of Rectangular Shape (lbh): 40x40 mm, 5x30 mm, 5x20 mm
Lower Specification(material)	EN 31 Steel
Lower Specification (Hardness)	lower standard a 60 HRC hardness
Stroke Length Range	10-20-30 fixed.
Load Range	Range of Loads 5-100 N (In the step of 5N)
Temperature Range	Ambient temperature 0 to 200 degrees Celsius (For Both Lubrication).
Frequency/Speed Range	1-20Hz Frequency (Speed) Range (1200 rpm) Least count: 1 rpm, Sensor, and Proximity Sensor
Frictional Force	0.1-100N Frictional Force Sensor: Piezo Sensor; Lowest Count: 0.1N
Range of Wear Measurement	2 mm, lowest count 1 micron
Water-Supply	Water flow rate: 2–5 lpm. There is an internal connection provision built in, and while heating, the outside faucet is connected to the water supply.
Power	230V* 1 Φ*50Hz, 8A (For Tester)

stiffness, excellent electrical performance, and chemical resistance. Carbon fiber epoxy laminate has a much higher strength-to-weight ratio than steel and aluminium alloys (Dal Lago et al., 2019; Santos et al., 2024; Patel et al., 2024). Adding nano-fillers to the epoxy matrix is a good way to make new materials with the benefits of both epoxy and nano-materials (Seidi et al., 2020; Lashgari et al., 2021).

The weight percentages of several composites in this work are added to epoxy resins coating material with a set quantity of ceramic particles to enhance the mechanical and tribological properties of the coating.

Material and Methods

Methodology of Experiment

There are many ways to improve the way a product, process, or operation is made. Optimizing the rate of wear can be done in a number of ways. Sometimes, combining many methods is necessary to get statistically significant results, which can lead to better conclusions and suggestions (Giliopoulos et al., 2020; Deng et al., 2019). Build Test Fix (BTF), Design of Experiment (DOE), and One Variable at a Time (OVAT) are all common ways to design a process or a product. However, BTF is a very basic and disorganized method. It is a way to design a process that focuses on making it better than the last time. DOE is a very good way to find out the effects of parameters because it changes several parameters at once. As more parameters are looked at, more new combinations need to be made. DOE can't control each factor separately, so it uses statistical data instead (Deng et al., 2019; Kumar et al., 2019). In the one variable at a time (OVAT) method, only one parameter is changed at a time while all other parameters remain the same until the effect of a single parameter is measured (Gupta et al., 2018).

It is a very precise way to figure out what happens when you change the value of each parameter. It was found that reinforcement, load, and temperature had the most effect on the wear rate (Lashgari et al., 2021; Venkatachalam et al., 2020). Using observations, the Taguchi method was used to find the best process parameters (Li et al., 2018; Liew et al., 2021). To find the best range of parameters for the optimization research, an OVAT analysis was done.

The orthogonal array (OA) design has been chosen for the Taguchi method L9. The standard way to write OA is:

OA = Ln (Xm),

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Where n is the number of experiments, X is the number of levels, and m is the number of parameters being studied (Nakonieczny et al., 2020; Singh et al., 2018).

From the designs for 3 levels and 3 parameters that were available, L9 was chosen because it required the fewest experiments. ANOVA was used to find out how much each parameter affected the output. Analysis has been done with Minitab 18 software (Khatri et al., 2018; Bossin et al., 2020).

Experimental Machine Selection

In Table 1, the details of the Tribometer used in this study are listed. All the experiments were done at the Government Engineering College, Aurangabad, Maharashtra, India.

Figure 1. Tribometer Setup.

Selection of material

One of the most important things is how you choose the materials for experimental work. There have been a lot of studies on how to improve powder coating by improving process parameters (Seidi et al., 2020; Singh et al., 2018). TiO_2 nanoparticles are mixed with the epoxy coating to make it harder to wear down. This is done to improve the mechanical properties of the epoxy resins (Lashgari et al., 2021). Epoxy powder is known for how well it sticks to things and how long it lasts. This is why it is mostly used in the oil industry and in refrigerators because of how well it transfers heat (Kumar et al., 2019). It is also used in the auto industry. Nanoparticles are mixed with the epoxy coating to make it more resistant to wear. This also helps improve the mechanical properties of the coating (Dal Lago et al., 2019). There have been studies on how to mix nanoparticles evenly into epoxy composite coatings, but there haven't been many studies on how to mix nanoparticles into epoxy powder (Giliopoulos et al., 2020).

In this study, the epoxy powder coating is made with TiO_2 as a filler. Nano Research Lab Matrics Technologies Solutions in Tamil Nadu, India, gave titanium dioxide nanoparticles.

Figure 2. TiO2 Nanoparticles

Results and Discussion

The signal-to-noise ratio or main effects plot for means to figure out how temperature, load and reinforcement affect the wear rate of the output (Lou et al., 2021). Minitab 19 statistical software and Design Expert software have been used for this purpose. Models have been made of the rate of wear. ANOVA has been used to find out how each parameter affects the wear rate, and a linear regression model has been made to predict wear rate values (Liu et al., 2019).

Most of the time, you look at the signal-to-noise ratio or main effects plot for means to figure out how temperature, load and reinforcement affect the wear rate of the output. Minitab 18 statistical software and Design Expert software have been used for this purpose. Models have been made of the rate of wear. ANOVA has been used to find out how each parameter affects the wear rate and a linear regression model has been made to predict wear rate values.

Calculation of SN ratio

The SN ratio is used to normalize the experimental data within a specific range, and the response for the SN ratio "smaller is better" is selected (Singh and Jayswal, 2021).

Given below is the equation of Signal-Noise (S/N) ratio for the response:

$$S/N = -10\log 10\sum\frac{y2}{n}$$

Where y is the response value and n is the number of total experiments.

Similarly, Signal to Noise ratio values can be obtained for other experimental runs in the orthogonal array. The cumulative data for S/N ratio epoxy resins coating wear are calculated as shown in Table 2 (Rogachev et al., 2020; Caccia et al., 2018).

With the help of the Minitab 19 software, the values of the S/N ratio are found. All of the experiments show that there isn't much difference in the S/N ratio.

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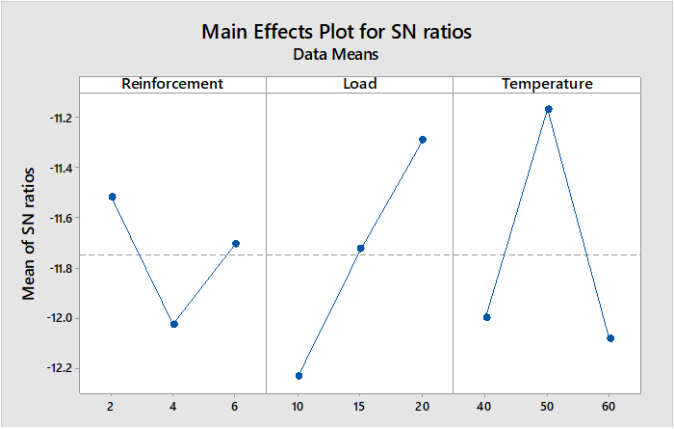
Table 2. L9 Signal to Noise Ratio of Specific Wear Rate.

Experiments	Inputs Factors			Output Responses	
Trial No.	Reinforcement (%)	Load (N)	Temperature (oC)	Wear rate (mm3/Nm* 10-3)	S/N Ratio
1	2	10	40	4.075	-12.2026
2	2	15	50	3.496	-10.8714
3	2	20	60	3.746	-11.4714
4	4	10	50	3.985	-12.0086
5	4	15	60	4.117	-12.2916
6	4	20	40	3.882	-11.7811
7	6	10	60	4.213	-12.4918
8	6	15	40	3.987	-12.0129
9	6	20	50	3.394	-10.6142

Main Effects of Wear Rate

Graph 1 shows the main effects plot from S/N ratios.



Graph 1. Main Effects Plot for S/N Ratio.

The Main Effect plot for the S/N ratio of epoxy resins powder with TiO_2 is shown in Graph 1. The optimally measured response is the level of a factor that has the highest SN ratio. The best wear rate parameters were 2% TiO_2 (level 1) 20N of load (level 3) and 50°C temperature (level 2).

Analysis of Variance

ANOVA is a statistical method for figuring out how well a number of different variables fit together. With a confidence level of 95%, or P values of less than 0.05, the results were found. It also shows how much each element contributed and how much it changed, which shows which factor had the biggest effect on the result.

fLN = N-1 gives the number of degrees of freedom as a whole.

Here's how to figure out degrees of freedom for residual error:

DF= (fLN) – (Sum of DF of all the terms included in the model)

In this study, a standard L9 array with three levels and four parameters is used. In this study, the load, the sliding distance, the temperature and the reinforcement are the four process parameters that were chosen.

Total fLN degrees = N-1 = 9-1 = 8

Each parameter has three levels, which means it has two degrees of freedom.

DF for residual error = 8-(2+2+2+2) = 0

In ANOVA, you divide the sum of squares by the number of degrees of freedom to get the adjusted mean square. Since residual error has no degrees of freedom, it is not possible to figure out its mean square.

Table 3. ANNOVA Result.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Reinforcement	2	0.074858	0.037429	20.06	0.047	11.89
Load	2	0.261335	0.130667	70.05	0.014	41.54
Temperature	2	0.289176	0.144588	77.51	0.013	45.96
Error	2	0.003731	0.001865			
Total	8	0.629100				

Table 4. Model Summary.

S	R-Sq	R-Sq (adj)
0.0432	99.41%	97.63%

Development of Regression Model for Wear Rate

Design Expert v13 is utilized to create a regression model. By substituting the experimental values of the parameters into the regression equation, wear rate values for all levels of study parameters can be predicted. The correlation between predicted and experimental values of wear rate is also demonstrated via graphical representation. Using design expert v13 software, a

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mathematical model for reinforcement, temperature and frequency is calculated and regression analysis is performed to obtain the predicted value of wear rate.

Regression Equation:

Wear rate = 4.300 + 0.0231 [Reinforcement] - 0.0417 [Load] + 0.0022 [Temperature]

Table 5 shows a comparison between the wear rate measured in the lab and the wear rate predicted by a mathematical equation.

Table 5. Experimental and Predicted Values of Wear rate.

Sr. No.	Experimental value	Predicted value	Error %
1	4.075	4.017	1.44
2	3.496	3.830	8.72
3	3.746	3.644	2.79
4	3.985	4.085	2.44
5	4.117	3.898	5.61
6	3.882	3.646	6.47
7	4.213	4.153	1.34
8	3.987	3.901	2.20
9	3.394	3.714	8.61

The difference between the calculated values for surface roughness and the experimental values for each experience was found to be less than 10%. We can therefore say that the regression equation that was made is correct. Graph 2 is a picture of the experimental data and the values those were calculated using the regression equation.

Confirmation of Experiment Result

In Table 8, we can see the difference between the value of the wear rate from the confirmation experiment and the value predicted by the regression model.

Table 6. Confirmation Experiment Result.

Parameter	Experimental value	Predicted value	Error %
Wear rate	3.292	3.622	9.11

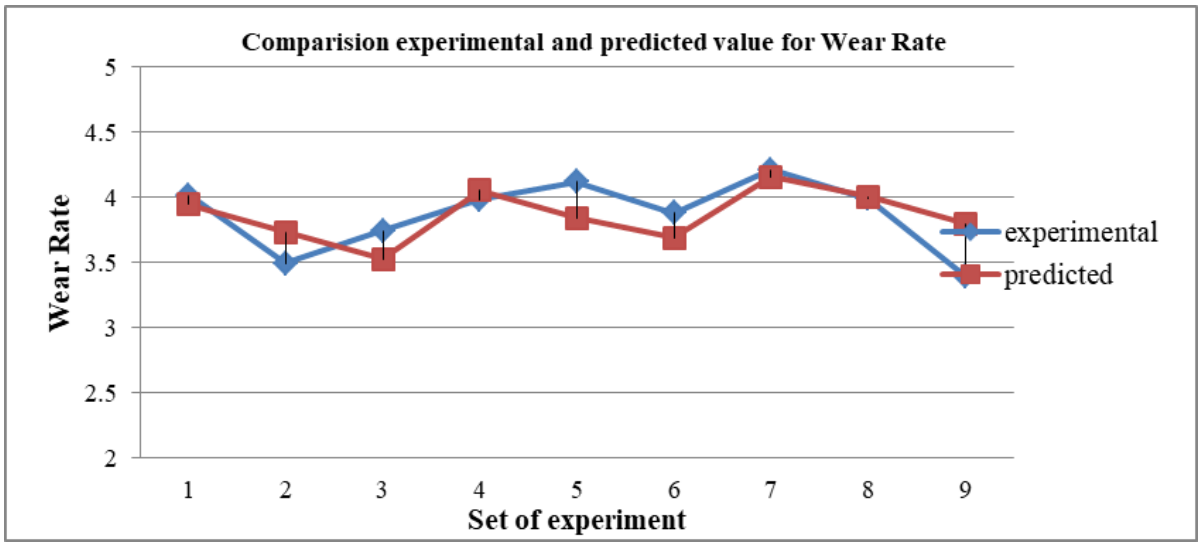
Keeping the parameters at the best levels suggested by the Taguchi method, a confirmation experiment was done, and the wear rate was compared to what the regression model predicted while keeping the parameters at the same levels. The difference between the actual result and the one that was predicted is 9.11%. This shows that the experimental value and the estimated value are similar.

Conclusions

In this study, the effects of operating parameters like Reinforcement, Load and temperature on the optimization of epoxy resins with TiO2 were looked into using the Taguchi Method following the conclusions:

#Optimization Results: The Taguchi method identified the optimal parameters for minimizing wear rate as 2% reinforcement, 20 N load, and 50°C temperature.

#Significant Factors: ANOVA analysis revealed that temperature, load, and reinforcement significantly impact the wear rate. Specifically, reinforcement contributed 11.89%, load contributed 41.54%, and temperature contributed 45.96% to the wear rate, emphasising the critical role of load and temperature in



Graph 2. Comparison between Experimental and Predicted Values of Wear Rate.

wear behaviour.

#Enhancement of Tribological Properties: Incorporating TiO_2 nanoparticles into the epoxy resin significantly improved its tribological properties. The reinforced composites exhibited a lower wear rate compared to pure epoxy resin, indicating that TiO_2 nanoparticles effectively enhance wear resistance.

#Validation of Results: Experimental validation confirmed the accuracy of the developed models, with less than 10% difference between predicted and experimental wear rate values. This high level of accuracy underscores the reliability of the regression model for predicting wear rates under various operating conditions.

#Practical Implications: The findings suggest that optimizing the content of TiO_2 nanoparticles, along with controlling load and temperature, can lead to the development of epoxy resin composites with superior wear resistance. This has practical implications for industries where enhanced durability and wear resistance of materials are crucial, such as the automotive and aerospace sectors.

Conflict of interest

None

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